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FUNCTIONAL PEARL

Linear, Bounded, Functional Pretty-Printing

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Abstract
We present two implementations of Oppen’s pretty-printing algorithm in Haskell that meet the efficiency of Oppen’s imperative solution but have a simpler, clear structure. We start with an implementation that uses lazy evaluation to simulate two co-operating processes. Then we present an implementation that uses higher-order functions for delimited continuations to simulate co-routines with explicit scheduling.

1 Introduction
Over 25 years ago Derek Oppen (1980) published an imperative pretty-printer that formats a document nicely within a given width. The algorithm is efficient: it takes time linear in the size of the input and is independent of the given width. Furthermore, the algorithm is optimally bounded, that is, for a partial input it already produces that part of the output for which no further inspection of the input is necessary. Oppen’s work inspired numerous pretty-printing libraries, in particular several Haskell libraries (Hughes, 1995; Peyton Jones, 1997; Wadler, 2003); all of these, however, are less efficient than Oppen’s. Then Chitil (2001; 2005) presented a purely functional Haskell implementation that has all the nice properties of Oppen’s original algorithm. That implementation, however, uses an intricate lazy coupling of two double-ended queues; it is quite complex and requires a special, modified implementation of double-ended queues.

The key problem is that information about what is to be printed and information about how it is to be printed does not become available at the same time. In this pearl we present more straightforward implementations. We start in Section 3.2 with a solution that makes sure that the information about how to format groups of text is passed to the place where we know what to format; we end in section 3.3 with a solution that builds functions that know what to print and calls these functions once it is known how to format. Our first solution (Swierstra, 2004) relies heavily on lazy evaluation, whereas in the last one (Chitil, 2006) the scheduling of the necessary computation has been made completely explicit.
2 Problem Description

2.1 The basic combinators

We will present the different versions — each of which can be seen as a deforested interpreter of a data type describing the structure to be printed — of our algorithm as instances of the following class, which closely follows the interface introduced by Wadler (2003):

```haskell
type Indent = Int     -- zero or positive
type Width = Int      -- positive
type Layout = String

class Doc d where
  text :: String → d
  line :: d
  group :: d → d
  (<>) :: d → d → d
  nest :: Indent → d → d
  pretty :: Width → d → Layout
  nil :: d
  nil = text ""
  prettyIO :: Doc d ⇒ Width → d → IO ()
  prettyIO w d = putStrLn (pretty w d)
```

Each instance of the class Doc describe a way to format documents within a given line width (to be referred to as $w$). The function text produces a primitive document containing just the String argument, line indicates a potential line break, and the operator <> concatenates two documents. The function nest is used to control indentation; it increments the indentation of the document in its second argument by its first argument. Finally, the function pretty renders a document of type $d$ given a width of type Width, and prettyIO finally prints it.

How a document is to be formatted is governed by the group and line combinators. All line markers directly contained in a group are to be either formatted as a space or as a newline with indentation. In the first case we say that the group is formatted horizontally, otherwise vertically. All groups contained in a horizontally formatted group are to be formatted horizontally too. All “top level” line markers are to be printed as newlines, i.e. the implicit top group is to be formatted vertically.

The problem to be solved is to find the “best” layout from the set of layouts described by a document. We define what is “best” in Section 2.2. Some might consider the best layout to be the one that uses the least number of lines. However, such an optimality criterion does not admit any bounded implementation; the end of a document can influence a layout decision at the very beginning (Hughes, 1995). An efficient algorithm computing such a shortest layout has been given by Swierstra et al. (1999). Here we will consider greedy algorithms.

Example. We can define a simple layout for lists of integers

```haskell
toDoc :: Doc d ⇒ [Int] → d
```
\textbf{Functional pearl}

toDoc = (text "\[\)"
  \circ foldr (\(\) (text "]")
  \circ intersperse (group (text "," \(\) line))
  \circ map (text \circ show)

which gives the following result:

\[
> \text{prettyIO 60 (toDoc [1..40])}
= [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40]
\]

Because each line marker is contained in a separate group, it is formatted horizontally if and only if the text up to the next line marker still fits on the current line, and vertically otherwise (The combination of group and line corresponds to the “inconsistent blank” of Section 5 in (Oppen, 1980)). Further examples can be found in Wadler (2003).

\subsection{2.2 Straightforward implementations}

We first present a specification of our algorithm in a number of steps. We start with a basic specification. This specification is then refined to make it comply with Oppen’s original specification. Next we introduce extra efficiency requirements, which make the problem harder. The solutions to these new problems form the core content of this paper.

\subsubsection{2.2.1 Basic Specification}

We can produce our layout by a simple pre-order traversal of the document tree, i.e., the tree representing the group structure. During this traversal we keep track of space remaining on the current output line. At the end of each group we check whether it fits in the space available for this group.

To determine whether a group fits in the remaining space on a line, we compute its total length, i.e., the sum of all the lengths \(s_k\) of the text elements and the number of line markers contained in the group, as if the whole document was formatted horizontally. Because we want to compute sizes \(s_l\) for many segments, we maintain the accumulated length \(p_j\) for which the following invariant holds:

\[
\sum_{i \leq k < j} s_k = p_j - p_i
\]

Since the accumulated lengths of preceding elements correspond to the position of an element if the complete document were layed out horizontally we will refer to such values as positions:

\textbf{type} \hspace{1em} \textbf{Position} = \textbf{Int}

We start by defining an instance \textit{Spec} of \textit{Doc}, which models a document as a function of four parameters and three results:

\textbf{type} \hspace{1em} \textbf{Remaining} = \textbf{Int}
\textbf{type} \hspace{1em} \textbf{Horizontal} = \textbf{Bool}
type Spec = (Indent, Width) → Horizontal → Position → Remaining
      → (Position, Remaining, Layout)

To reduce the number of arguments in the algorithms to come, we have tupled the
Indentation of the document with the global Width. The argument of type position
is the position at the beginning of the represented document, and the result Position
the position at the end. The Horizontal argument indicates whether the embracing
group is to be formatted horizontally or vertically. The Remaining values keep track
of the free space on the “current output line”: the argument tells us how much is
available at the beginning and the result how much is still left at the end of the
“current document”. Our basic specification now reads as follows:

instance Doc Spec where
  text t  iw h p r = (p + l, r − l, t) where l = length t
  line   iw h p r = (p + 1, r1, l1) where (r1, l1) = newline iw h r
  (dl <> dr) iw h p r = (pr, rr, l1 + l2)
     where (p1, r1, l1) = dl iw h p r
                      (pr, rr, l2) = dr iw h pr r1

  group d  iw h p r = let w@(_, _) = d iw (pd − p ≤ r) p r in v
  nest j d (i, w) = d (i + j, w)
  pretty w d = let (_, l) = d (0, w) False 0 w in l

  newline (i, w) True r = (r − 1, [ ]; )
  newline (i, w) False r = (w − i, '\n', replicate i ' ')

This algorithm depends on lazy evaluation, because the definition of group uses a
cyclic binding which both defines the endpoint pd of group and uses it. This design
pattern in which part of the result of a call is used to compute one of its arguments
is also known from the famous Repmin problem (Bird, 1984). If the difference
between the begin- and endposition of a group does not exceed the free space at
the beginning of the group (pd − p ≤ r), we can format the group horizontally,
otherwise we have to resort to vertical formatting; we say that in such a case the
group extends beyond its maximal endpoint pd + r. In the definition of pretty the
whole document is applied to False, expressing that line markers appearing outside
any group are always to be formatted as line breaks with an initial indentation of
0.

One might be tempted to combine the definition of newline with that of line,
writing:

  line _  p True  r = (p + 1, r − 1, [ ]; )
  line (i, w) p False r = (p + 1, w − i, '\n', replicate i ' ')

This however fails. To choose between the two alternatives we need the value of the
Horizontal argument; but this argument usually depends on an expression pd − p ≤ r,
since this line may be part of a group, so it depends on the final position pd of
this group, and this is a value which is returned by the call and thus cannot be
used in deciding which alternative to take. Despite the fact that both alternatives
contribute the same value to the position (p + 1), the last formulation of line forces
us to make a choice between the two alternatives too early.
2.2.2 Normalising documents

Although probably not immediately obvious the given specification may produce lines longer than \( w \):

```haskell
> prettyIO 6 (group (text "Hi" <> line <> text "you") <> text "!!!"))
Hi you!!!
```

whereas we would prefer:

Hi
you!!!

The cause of this behaviour is that a group that still fits on a line may be followed by further text without a separating `line` marker, and thus will end up on the current line even if it extends beyond the end of the line; unfortunately the fact that a group fits does not imply that all its trailing `text` elements will also fit. In our example formatting the preceding group vertically would have avoided lines becoming longer than \( w \). A simple preprocessing step deals with this problem, by moving all `text` elements to the group to which their nearest preceding `line` marker belongs if it exists. There are two ways to look at our documents: either as sequences of `text` elements separated by `line` markers, or as tree structures built by `group` and `nest` operators, where each node contains additional `text` elements and `line` markers.

So before formatting we first apply a document transformation that moves all `text` elements such that no consecutive sequence of them extends beyond a group. The transformation is based on the following laws:

\[
\begin{align*}
group (t <> d) &= t <> \group d \\
group d <> t &= \group (d <> t) \\
nest j (t <> d) &= t <> \nest j d \\
nest j d <> t &= \nest j (d <> t) \\
(d_1 <> d_2) <> d_3 &= (d_1 <> (d_2 <> d_3))
\end{align*}
\]

We introduce \( \text{Norm } d \) as a second instance of \( \text{Doc } d \). A \( \text{Norm } d \) is a function returning two elements of type \( d \): one containing the leading sequence of `text` elements to be included in a preceding group, and the other the rest of the document. Furthermore, each \( \text{Norm } d \) takes an argument, containing the leading text of its successor:

```
type Norm d = d \rightarrow (d, d)
```

In this way we have introduced a backwards travelling accumulating document, containing a sequence of text elements (passed to it predecessor in the argument \( tt \), trailing text). At each `line` marker we insert these accumulated text elements. As a result, in a normalised document each group starts with a `line` marker if it contains elements at all.

```
instance Doc d \Rightarrow Doc (Norm d) where
  text t tt = (text t <> tt, nil )
  line tt = (nil , line <> tt)
  (d_1 <> d_r) tt = let \( (td_1, sd_1) = d_1 \quad td_r, \quad sd_r = d_r \quad tt \)
                   in \( (td_1, sd_1 <> sd_r) \)
  group d tt = mapsnd group (d tt)
  nest j d tt = mapsnd (nest j) (d tt)
```

\[
\text{pretty w d} = \begin{array}{l}
\text{let } (td, sd) = d \text{ nil in pretty w (td <> sd)} \\
\end{array} \\
\text{nil} &= (tt, \text{nil}) \\
\text{mapsnd } f (x, y) &= (x, f y)
\]

### 2.3 Extra Requirements

#### 2.3.1 Optimally Bounded

If the outer element of the document is a `group`, our straightforward algorithm `Spec` traverses the complete document tree before emitting any result; this is definitely undesirable for large documents. So we introduce some extra requirements.

Our straightforward algorithm `Spec` is fully strict, as the following computation demonstrates:

\[
> \text{prettyIO 4 (group (text "Hi" <> line <> text "you" <> undefined) :: Spec)}
\]

Program error: `{undefined}`

However, after having seen the strings "Hi" and "you" we can already conclude that together they do not fit in a line of width 4. So output can be produced without inspecting any further elements, resulting in:

\[
> \text{prettyIO 4 (group (text "Hi" <> line <> text "you" <> undefined) :: ??? )}
\]

Hi
you
Program error: `{undefined}`

Based on a prefix of the document of size \(w\) we can always decide how to continue formatting, because any group wider than the width-limit has to be formatted vertically. We say that `pretty` is `bounded` if look-ahead into the input is limited by the width \(w\). We require our final program to be even optimally bounded, i.e., any part of the output that can be produced without touching a ⊥ element in the input has to be produced.\(^1\) Our `Spec` and `Norm Spec` instances do not fulfill the boundedness requirements, because to determine the total horizontal size of a group it requires all group elements to be defined.

### 2.3.2 Complexity

Of course, we want our algorithms to be in the class \(O(n)\), where \(n\) is the number of elements in the input. However, with increased line width the length of the output, when seen as a single long string, may increase, because we will generally have deeper nestings and thus we may generate more white space. We could avoid this problem by representing a layout as a list of indentation-line pairs, \([([\text{Indent}, \text{String}])]\), as in (Hughes, 1995). However, for simplicity and practical applicability we produce a single string and just consider generation of a sequence of white space as a constant time operation. Given this caveat our specification

\(^1\) To be precise, we do not consider partial strings. The argument of `text` is considered as an atomic value that is added to the layout in one step.
is linear and we have to ensure that this linearity remains fulfilled once we find
optimally bounded solutions.

One may try to transform Spec into an optimally bounded version by having a
document return a (lazily constructed) list \( (ls :: [Int]) \) containing the sizes of the
text elements and line markers in a group in which the lengths of earlier elements
come first, and by replacing the test \( p_d - p \leq r \) by an incremental test \( ls' \text{pruning}' r \),
which fails as soon as the accumulated sizes exceed the available free space:

\[
\text{pruning} :: [Int] \rightarrow \text{Remaining} \rightarrow \text{Bool}
\]

\[
(s : ss)' \text{pruning}' r = (s \leq r) \land ss' \text{pruning}' (r - s)
\]

\[
[\text{ }]' \text{pruning}' r = \text{True}
\]

Although this modification makes the algorithm optimally bounded, its com-
plexity now suddenly depends on \( w \), because the pruning is done for each group
individually: because the result \( ls \) of a document in a group will be traversed both
by \text{pruning} when deciding whether this group fits, and is returned as part of the \( ls \) of
the embracing groups, pruning with nested groups will traverse the same (parts of)
lists. Especially with deeply nested groups this becomes a problem. For a document
of the shape

\[\text{group (group (group (....}}\]

the lists of the inner groups will be prefixes of their embracing groups. The pruning
process will become a linear search for the first one that passes the \text{pruning} test.
Thus the complexity of our solution becomes dependent on \( w \).

At this point we may point out a subtlety. One might be inclined to think that if
the function \text{pruning}, as part of the pruning process of the father group, consumes
all the elements contributed by a subgroup without failing, that subgroup will fit
irrespective of the decisions taken for its ancestors. Unfortunately, this is not the
case as the following example demonstrates:

\[
\text{prettyIO 15}
\]

\[
(\text{group (text "this" }< > \text{nest 9 (line }< > \text{group (text "takes" }< > \text{line }< > \text{text "four"))})
\]

\[
< > \text{line }< > \text{text "lines"})
\]

results in:

\[
\text{this}
\]

\[
\text{takes}
\]

\[
\text{four}
\]

\[
\text{lines}
\]

Because the outer group does not fit, the inner group is suddenly indented by 9
spaces. As a consequence the inner group does not fit either! So in order to take a
decision for an inner group, we always first have to decide whether its embracing
groups fits. Only then will we precisely know how much free space is still left on
the line for this inner group.
3 Solutions

In this section we will present a sequence of solutions to the pretty printing problem. Before going into the actual solutions we will explain why we will use double-ended queues in all our solutions.

3.1 Double-ended queues

We have seen how the idea of pruning avoids always scanning a complete group before deciding whether it fits. The problem is how to share the scanning of a group with the enclosed groups and thus to avoid the observed recomputations, because it is this aspect that makes the pruning solution depend on the width $w$. The fundamental idea, due to Oppen (1980), is to have two processes traverse the document: a scanning process determines for all groups whether they fit and a printing process uses that information to produce the pretty layout. Pruning ensures that the scanning process never goes far ahead of the printing process.

To explain more precisely what the two processes do, we refer to Picture 1. In this picture we have sketched the group structure (without the line and text elements) of some example input. We distinguish four kinds of nodes: decided, pending, traversed and untouched. The kinds of nodes change while both processes traverse the tree in prefix order:

1. Nodes that form part of a group which we know how to format. We indicate
these as decided nodes. A decided group can be traversed by the printing process up to the first pending or traversed subnode.

2. Nodes that have been traversed by the scanning process but are not decided yet; they come in two kinds:
   (a) Nodes in groups that have been completely traversed by the scanning process.
   (b) Nodes corresponding to the root of a subgroup we have entered, but not yet left. We call these nodes pending.

3. Nodes that have not been inspected yet (untouched).

In the picture we have indicated the path consisting of pending group nodes that leads from the top pending group to the point up to where the scanning process has proceeded. When traversing the tree, this path will grow and shrink as a result of pruning, and entering and leaving groups. We will refer to these nodes as the dequeue, as it is a double-ended queue that can grow and shrink at the end and shrink at the top. Each node in the second category above corresponds to an open question: for the pending node we expect an answer from the scanning process, and for the traversed node we can decide once we know the decision for its father, so we can compute how much space is available for the group. In the latter case the situation is similar to the situation as handled in our original specification; traversed implies that the total horizontal space needed for the group is known.

The first problem we address is what extra information we have to maintain while investigating whether the top pending group fits, such that when we discover — when pruning — that it does not fit, we can continue with the investigation of the next pending group without reinspecting any values.

We focus on the path with nodes labelled pending in the picture. When scanning several things may happen:

- We may conclude that the top pending group does not fit. Then we can take the decision for all its traversed children in the same way as we did in Spec: we know their horizontal sizes. So we can print all the elements up to the group node that is next in the dequeue, without any further scanning. This next group becomes the new top pending group.
- We may have traversed the innermost group, i.e., the group corresponding to the last element of the dequeue; in this case we can mark the group as traversed and remove it from the end of the dequeue.
- We encounter a new group, in which case we extend the dequeue at the end with an extra element.

We introduce the following pseudo data type for double-ended queues. Okasaki’s banker’s dequeue implementation (Okasaki, 1998) supports all operations in \(O(1)\) amortised time.

---

2 We will use the \(<\) only for matching, but never as a constructor.
data Dequeue e = ⟨⟩ -- the empty dequeue
  | e < Dequeue e -- prepend an element
  | Dequeue e >>= e -- append an element

When we introduced the function pruning, the values to be pruned were collected and moved to the start of the group; instead of this we build solutions in which we carry along a dequeue containing the current state of the scanning process, and we update this dequeue based on the result of pruning the values we encounter. We perform a little bit of the pruning work for the top pending node whenever we encounter a new element that takes up space.

We will now present a sequence of solutions, with increasing efficiency, but also an increasing intricacy.

3.2 Bringing the arguments to the printing functions

Let us suppose for a moment that the scanning process manages to compute the Horizontal (i.e. the Boolean indicating how to format a group) information efficiently by carrying the dequeue along when traversing the tree. Then this creates a new problem: the Horizontal values that become available while scanning have to be made available to the printing process.

Our first step is to extend the algorithm with the computation of the complete list of all needed Horizontal values (i.e. the Boolean values for all the groups), listed in prefix order. In the function pretty at the root of the overall computation we pass this list back as an argument to the root document, so it can be consumed in the printing process; this design pattern was also used in the group function in the Spec instance. The tricky part however is here that we also have an information flow in the other direction:

1. The printing process computes the layout. It consumes the list of Horizontal values and additionally returns Remaining values.
2. The pruning process computes the positions \( p \), reads the Remaining values, and thus produces the list of Horizontal values.

We use lazy evaluation to schedule the two parallel processes, each producing output for the other.

Looking at the picture we see that for each group we have entered but not yet left we have a node in the dequeue. In this node we store the relevant information for each pending group: its maximal endpoint \( p + r::Position \) and its ( lazily evaluated) Horizontal values for its traversed descendant groups.

\[
\begin{align*}
\text{type } \text{Horizontals} & = [\text{Horizontal}] \\
\text{type } P & = \text{Horizontals} \quad -- \text{Produced by the pruning process} \\
\text{type } C & = \text{Horizontals} \quad -- \text{Consumed by the printing process} \\
\text{type } Dq & = \text{DeQueue} (\text{Position}, \text{Horizontals})
\end{align*}
\]

We extend our algorithm such that it carries along two extra threaded variables: a \( Dq \) on behalf on the pruning process and the list of unconsumed \( \text{Horizontals} \) on behalf of the printing process. Furthermore, we return the global list of \( \text{Horizontals} \) to be used in \text{pretty} as part of the result:
We define three functions that update the Dq structure, two of which may additionally return newly found Horizontal information:

\[
\begin{aligned}
\text{enter} &:: \text{Position} \rightarrow \text{Dq} \rightarrow \text{Dq} \\
\text{leave} &:: \text{Position} \rightarrow \text{Dq} \rightarrow (\text{Dq}, \text{P}) \\
\text{prune} &:: \text{Position} \rightarrow \text{Dq} \rightarrow (\text{Dq}, \text{P})
\end{aligned}
\]

When descending into a new group we update the Dq by appending the maximal endpoint of this group, while at the same time recording that we have no information on its traversed children yet (the empty list []):

\[
\text{enter mep } q = q \triangleright (\text{mep}, [])
\]

The function \text{leave} updates the Dq and possibly returns newly found P. The function distinguishes three cases, based on the length of the dequeue:

0: We have already discovered that the group we are leaving does not fit, and so we learn nothing new.

\[
\text{leave } p \langle \rangle = (\langle \rangle, [])
\]

1: We are leaving the current group. Since this node was not pruned away yet, we conclude that the group fits. We also incorporate the Horizontals computed for its children into the list of answers, so they show up in their correct position.

\[
\text{leave } p \langle \rangle \triangleright (\text{mep}, \text{hs}) = (\langle \rangle, \text{True} : \text{hs})
\]

>1: The last pending group changes status to traversed. We incorporate this information, together with the information about its children into the node of the group one level up, to be included later in the list of answers we are constructing:

\[
\text{leave } p \langle \rangle \triangleright (\text{mep}, \text{hs}) \triangleright (\text{mep}, \text{hs}) = (\langle \rangle \triangleright (\text{mep}, \text{hs}) \triangleright (\text{mep}, \text{hs}) =
\]

\[
((\langle \rangle \triangleright (\text{mep}, \text{hs}) \triangleright (\text{mep}, \text{hs}) =
\]

\[
\text{prune } p \langle \rangle = (\langle \rangle, [])
\]

\[
\text{prune } p q \triangleright ((\text{mep}, \text{hs}) \triangleright qq) =
\]

\[
\begin{aligned}
| p \leq \text{mep} & = (q, []) \\
| \text{True} & = \text{let } (q', \text{hs new}) = \text{prune } p \text{ qq } \text{ in } (q', \text{False} : \text{hs} \triangleright \text{hs new})
\end{aligned}
\]

Using these auxiliary functions we can now formulate a solution which fulfills all requirements. In the case of a group we remember the current head of the list of horizontal information, which tells us how the parent group is to be formatted, and
put this back at the head of the tail of the returned value, from which the children have all taken away their Horizontal elements. The tail removes the Horizontal value for the current group, which has served its purpose and is thus no longer needed.3

instance Doc Lazy where
text t \text{iw} (p, dq, hs, r) = ((p + l, dq', hs, r - l), t, as) \text{where} l = \text{length } t 
(dq', as) = \text{prune } (p + l) \ dq
line \text{iw} (p, dq, h, s \ r) = ((p + 1, dq', hs, r'), l', as) \text{where} (dq', as) = \text{prune } (p + 1) \ dq 
(r', l') = \text{newLine } \text{iw} (\text{head } hs) \ r

(d_l <> d_r) \text{iw state} 
= (\text{state}_r, l + l, as_l + as_r) \text{where} (\text{state}_l, l, as_l) = d_l \text{ iw state} 
(\text{state}_r, l_r, as_r) = d_r \text{ iw state}_l

group d \text{ iw} (p, dq, \sim(h : hs), r) = ((pe, dq', h : tail hsd, r_d), l_d, as_d + as')
\text{where} ((pe, dq_{d, hsd}, r_d), l_d, as_d) = d \text{ iw} (p, (\text{enter } (p + r) \ dq), hs, r) 
(dq', as') = \text{leave pe dq_d}
nest j d (i, w) = d (i + j, w)
pretty w d = \text{let} \ (- l, as) = d (0, w) (0, \langle\rangle, (False : as), w) \text{in } l

For the function group lazily accessing head hs and tail hs is essential. When encountering a new group we may still be scanning for one of its remote ancestors, and thus the constructor (: of hs cannot be matched upon, because this part of the list has not been produced yet. One might find this code quite elaborate. It was originally written using an attribute grammar, in which all the different aspects are described separately. The attribute grammar based definition can be found in a technical report by Swierstra (2004).

We implemented two co-operating sequential processes that are coupled through lazy evaluation. The P list that is produced in the functions leave and prune is passed as an argument to the function pretty and is being consumed in the actual construction of the Layout and thus serves as a synchronising buffer. The communication from the printing process to the computation of the P list is a bit more subtle: when storing the maximal endpoints p + r in the dequeue, the value of r will in general not be known yet; only when we have concluded whether the parent groups fit and have produced the output up to the beginning of the group, this value gets known. Lazy evaluation enables us to refer to this yet unknown value.

3.3 Bringing the printing functions to the arguments

The question arises whether we can make the exchange of information between the scanning and the printing processes more explicit, thus changing from a parallel

3 For the sake of clarity we have encoded all list concatenations explicitly. In the actual implementation these have to be replaced by more efficient versions.
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processes view to a co-routine view. The answer is affirmative: instead of computing
the \( P \) list and bringing it to the printing part, the scanning co-routine can build for
each group a function that constructs the actual layout (prints in our terminology),
based on its Horizontal parameter. So instead of storing Horizontal values in the
dequeue we store printing functions, to be called once we know their ‘horizontality’.
Thus evaluation of the printing and scanning co-routines is interleaved.

We introduce the following types:

\[
\begin{align*}
\textbf{type} & \ Out & = \text{Remaining} \to \text{Layout} \\
\textbf{type} & \ OutGroup = \text{Horizontal} \to \Out \to \Out
\end{align*}
\]

The type \( \Out \) is the type of a function that prints a suffix of a document, that is,
from a given point to its end; the function takes as argument the remaining free
space on a line and produces a \( \text{Layout} \). The type \( \OutGroup \) is used to represent
the postponed construction of the layout corresponding to the traversed part of a
group. It takes three arguments, one indicating how the group is to be formatted,
a continuation for the rest of the document, and the remaining free space at the
beginning of this group. The latter value remains synchronised with the actual
output produced, and the updated value is passed on to the continuation.

Instead of storing Horizontal values in the dequeue, we now store values of the
type \( \OutGroup \), which represent postponed printing:

\[
\begin{align*}
\textbf{type} & \ Dq & = \text{DeQueue} (\text{Position}, \OutGroup) \\
\textbf{type} & \ TreeCont & = \text{Position} \to Dq \to \Out \\
\textbf{type} & \ Cont & = (\text{Indent}, \text{Width}) \to \TreeCont \to \TreeCont
\end{align*}
\]

The algorithm mainly initialises and combines delimited continuations:

\[
\text{instance Doc Cont where}
\]

\[
\begin{align*}
\text{text } t & \ iw = \text{scan l outText} \\
\text{where} & \\
\text{l} & = \text{length } t \\
\text{outText } c r & = t + c (r - l) \\
\text{line } (i, w) & = \text{scan 1 outLine} \\
\text{where} & \\
\text{outLine True } c r & = \text{inc } c (r - 1) \\
\text{outLine False } c r & = ' ' : \text{replicate } i ' ' + c (w - i) \\
\text{(dl <> dr)} & \text{iw} = d l \text{iw} \circ d r \text{iw} \\
\text{group } d & \text{iw} = \lambda c p dq \to d \text{iw (leave c) p (dq} \triangleright (p, \lambda h c \to c)) \\
\text{nest } j d & (i, w) = d (i + j, w) \\
\text{pretty w d} & = d (0, w) (\lambda p dq r \to "") 0 \langle \rangle w \\
\text{nil } & \text{iw} = \lambda c \to c
\end{align*}
\]

When scanning \text{text} and \text{line} documents we distinguish between the following
cases:

- We already know that the group they belong to does not fit (represented by
the dequeue being empty). In this case we can immediately print the element.
- We are still waiting for this information to become available. In this case we
remember the printing obligation in the last element of the dequeue.

\[
\text{scan :: Width } \to \OutGroup \to \TreeCont \to \TreeCont
\]
\[ \text{scan \ out \ } c \ p \ (\{\}) = \text{out } \text{False} \ (c \ (p + l) \ (\{\})) \]

\[ \text{scan \ out \ } c \ p \ (dq \triangleright (s, \text{grp})) = \text{prune} \ c \ (p + l) \ (dq \triangleright (s, \lambda h \rightarrow \text{grp} \ h \circ \text{out} \ h)) \]

Every time scanning increases the current position and the dequeue may be non-empty, prune checks whether a pending dequeue element can be printed:

\[ \text{prune} :: \text{TreeCont} \rightarrow \text{TreeCont} \]

\[ \text{prune} \ c \ p \ (\{\}) \ r = c \ p \ (\{\}) r \]

\[ \text{prune} \ c \ p \ dq \triangleright ((s, \text{grp}) \lhd dq') \ r \mid p > s + r = \text{grp} \ \text{False} \ (\text{prune} \ c \ p \ dq') \ r \mid \text{True} = c \ p \ dq \ r \]

Finally, at the end of a group the last dequeue element — if it has not already been pruned away — is printed or the print obligation is merged with the element for the surrounding group.

\[ \text{leave} :: \text{TreeCont} \rightarrow \text{TreeCont} \]

\[ \text{leave} \ c \ p \ (\{\}) = c \ p \ (\{\}) \]

\[ \text{leave} \ c \ p \ (\{\}) \triangleright (s_1, \text{grp}_1) = \text{grp}_1 \ \text{True} \ (c \ p \ (\{\})) \]

\[ \text{leave} \ c \ p \ (pp \triangleright (s_2, \text{grp}_2) \triangleright (s_1, \text{grp}_1)) = c \ p \ (pp \triangleright (s_2, \lambda h \rightarrow \text{grp}_2 \ h \ (\lambda r \rightarrow \text{grp}_1 \ (p \leq s_1 + r) \ c \ r))) \]

In contrast to our previous solution, how the scanning co-routine treats the elements of a group depends on whether the dequeue is empty. This distinction is required for our more explicit scheduling of the computation, which does not use lazy evaluation anymore. This solution also works in a strict setting.

4 Conclusions

As mentioned in the introduction many have tried to derive a backtrack-free implementation of Oppen’s algorithm. Especially Hughes (1995) and Wadler (2003) employed algebraic techniques, and one may wonder why they did not come up with a solution satisfying all nice properties. We think the answer is that we are dealing here with two mutually recursive processes, which run asynchronously. This is not easy to express in a purely algebraic style.

We used the interface designed by Wadler; his implementation is bounded, but not optimally bounded (Section 9 of (Chitil, 2005) demonstrates the difference).

What is the difference between Chitil’s (2001; 2005) first pretty printing solution and our solutions presented here? It is the way in which the scanning process informs the printing process about whether a group is to be printed horizontally or vertically. Like our Lazy solution Chitil’s first solution passes for every group a Boolean Horizontal from the scanning process to the printing process. However, Chitil’s first solution is based on the idea that the printing process has passed the information what the Remaining space at the beginning of the group is to the scanning process and hence the Horizontal information should be passed backwards along the same way. The Remaining value of a group travels as part of the start position of the group through the dequeue to the point where the scanning process uses it to decide whether the group is to be formatted horizontally. Hence Chitil’s first solution uses a second dequeue with the same structure as the dequeue of pending group nodes but with reversed data flow to pass a Horizontal value back to its group in the printing process. In the middle of pretty printing parts of the
second dequeue do not yet exist, but the defined elements can still be accessed using the identical and fully defined structure of the first dequeue. The required close relationship between the two dequeues implies that no standard dequeue implementation can be reused, the special dequeue implementation is quite complex, and operations have a constant but high time cost.

Our solutions presented here use a single standard dequeue. The Lazy solution passes Horizontal information in a simple list to the printing process and the Cont solution directly constructs printing functions. The latter corresponds to the coroutine equivalent of our parallel processes view, which makes the scheduling of all the computations explicitly visible. All lazy evaluation is gone. Ideally, we would have liked to derive the second solution from the first; we did not manage to do so. We hope this pearl will inspire others to investigate the transformation from the parallel view into the co-routine view in other (less tricky) contexts.

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References


